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I. Kargapolova

Faculty of Geography, Moscow State University, Russia

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Abstract. The focus of this study was to determine river runoff impacts on channel evolution during the last centuries. Comparing a number of maps from the 18th–21th centuries and space images in concert with hydrological data we estimated natural trends, cycles and the intensity of channel formation for periods of high and low runoff. Our analysis for a long period of time enable us assessing mean and maximum rates of erosion and accumulation of river channels and bank dynamics under different conditions. Using links between runoff values and meander size we predict and reconstruct these for several Russian rivers. For forecast validation we use cases of high scale runoff change – water transfer from one basin to another.

1 Introduction

River runoff fluctuations is a determining factor for river channel formation, i.e. they determine trends, cycles and intensity of channel processes. Usually the impact of runoff fluctuations on river bed has been studied in geological time scale using palaeo methods (e.g. Vandenberghe, 1995; Panin et al., 1999; Sidorchuk et al., 2001). The main goal of our research is to estimate the river channel response in historical time scale based on documental sources such as old maps and hydrological data. In Russia this historical period is limited by the existence of old topographical maps, which dates back to the mid-XVIII century.

The comparisons and analyses of historical data allow us determining long-term features of river channel evolution in natural conditions and under human impact.

Correspondence to: I. Kargapolova
(ikargapolova@gmail.com)

2 Background

We studied three river systems from different Russian regions: the Oka and Moscow rivers in Russian central plain, the Severnaya Dvina and Vychegda rivers in the Russian north plain, and the Ob' and Tom rivers in the West Siberian Plain. The selected rivers have different discharge regimes and types of river channels (Table 1) and have been subjected to anthropogenic impacts in recent decades. For example, the Moscow and Ob' rivers are regulated by hydropower plants. Due to runoff regulation, intra-annual hydrograph changes and channel formative discharge decreases. As a result on the Ob River downstream the hydropower plant sedimentation process converts to erosion, secondary branches die and braiding channel turns to meander channel. On Tom' and Oka rivers a huge amount of sediments was dredged. That leads to channel erosion and water level reduction. As a result, annual inundation of floodplain isn't observed anymore. Water runoff on the Tom River is concentrated in main branches. The anthropogenic impacts on the northern rivers – Severnaya Dvina and Vychegda have not been very high. In these rivers the dredging along the waterways has not been extensive and it has been finished in end of the 20th century. And thereafter weak stable river channels have already returned to natural conditions. The study of these rivers provide an unique chance to evaluate natural trends of bed evolution since the 18th century. Most other major European rivers are under significant anthropogenic impact and hence do not allow such investigation.

3 Methods

For each river not less then 7 temporal intervals were selected, from the 18th century until present. For referencing and comparison of different maps and plans space images (Landsat ETM+, Terra Aster) for selected areas were mostly

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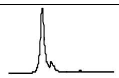
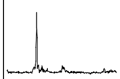
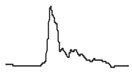
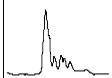
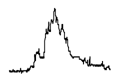
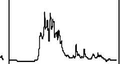
Table 1. Main characteristics of river discharge and type of channel.

Characteristic	River (station)					
	Oka (Kasimov)	**Moscow** (Pererva)	**Severnaya Dvina** (Abramkovo)	**Vychegda** (Fedyakovo)	**Ob** (Novosibirsk)	**Tom** (Tomsk)
Annual discharge, m^3/s	550	100	1930	1010	1740	1080
Av. maximum discharge, m^3/s	5000	750	11200	9370	5600	6200
Annual hydrograph						
Type of channel	Meanders	Meanders	Braids	Meanders and braids	Braids	Braids

used. Settlements, usually old buildings, churches, cloisters and bridges, denoted on all maps and plans, were used as benchmarks. For study areas without settlements, objects that most likely have remained at the same position within the last 200–300 years, such as rock capes, points of bedrock banks contraflexure, sometimes mouths of tributaries, oxbows etc., played the role of benchmarks.

Comparison of maps and space images made it possible to assess river channel migration rates with an accuracy of about 15–30 m, to estimate mean and maximum values of erosion and accumulation inside the channel as well as bank dynamics under different conditions from the 18th century until present.

4 River channel change

River bed changes were studied within the flood plain areas, where channel migration is free. The figures illustrate two main types of river channel transformations: braiding (most likely on large rivers), and meandering (medium and small rivers). We determine steps, cycles and intensity of their development during the last centuries.

The main transformation type of braiding channels are runoff migration between branches, bank erosion and flood area accumulation. Examples of braiding channel transformation on the Severnaya Dvina River (Fig. 1a, b), the Ob River (Fig. 1d) and Vychegda River (Fig. 1e, f) are presented on Fig. 1. Figure 1a and d illustrate the change of branch mastership – transfer of main water stream from one branch to another. Sediment accumulation, island enlarging and their migration upstream as well as regression of minor branches are shown on Fig. 1b. Figure 1e presents an example of braiding-meandering channel in the middle flow of the Vychegda River. The stream changed direction here as a result of meanders stretching and moved to the left branch.

The development of meanders (Fig. 1c, e, f) is clear and predictable. The life cycle of meanders consists of a number of stages. After the formation of the initial curve the meander curvature increases (Fig. 2) and reaches s-type form. Meander curvature is usually characterized by l/L ratio, where l is meander length and L is meander step. Shape, stream dynamics, rate and direction of meander movement change as the meander curvature increases (Makkaveev, 1955; Hickin, 1974; Zavadskiy et al., 2002; Chalov et al., 2004). The spur of the meander bursts and its "life" ends after curvature and water discharge reach their critical values (Fig. 1c).

The study of branch and meander migration within flood plain areas is extremely important because bank retreat rates may be as high as dozens of metres per year, so deformations can destroy intakes, buildings, pipelines, bridges etc. (Fig. 3). For instance, the horizontal retreat of eroded banks on the Vychegda River may be more then 20 m per year. As a result, Syktyvkar City, the capital of the Komi Region (Fig. 1e), is constantly confronted with the destruction of hydrotechnical buildings, especially intakes. Active formation of the Sharda branch is currently observed. Most likely, runoff will be fully concentrated in this branch, so Syktyvkar City may meet with water supply problems. The inverse case took place in Solvychegodsk Town (Fig. 1g). The river channel here has shifted towards the right bank, where the town is located. The increase of meander curvature has destroyed buildings including a unique ancient cathedral of the 15th century (Fig. 3, first photo). Despite banks are firmed and the river bed is intensively excavated, spring flood bank erosion goes on.

5 Main factors of river channel change

Main factors of river channel natural evolution may be divided into two groups: constant and changing. Such regional factors, geological, geomorphological, or some hydrological,

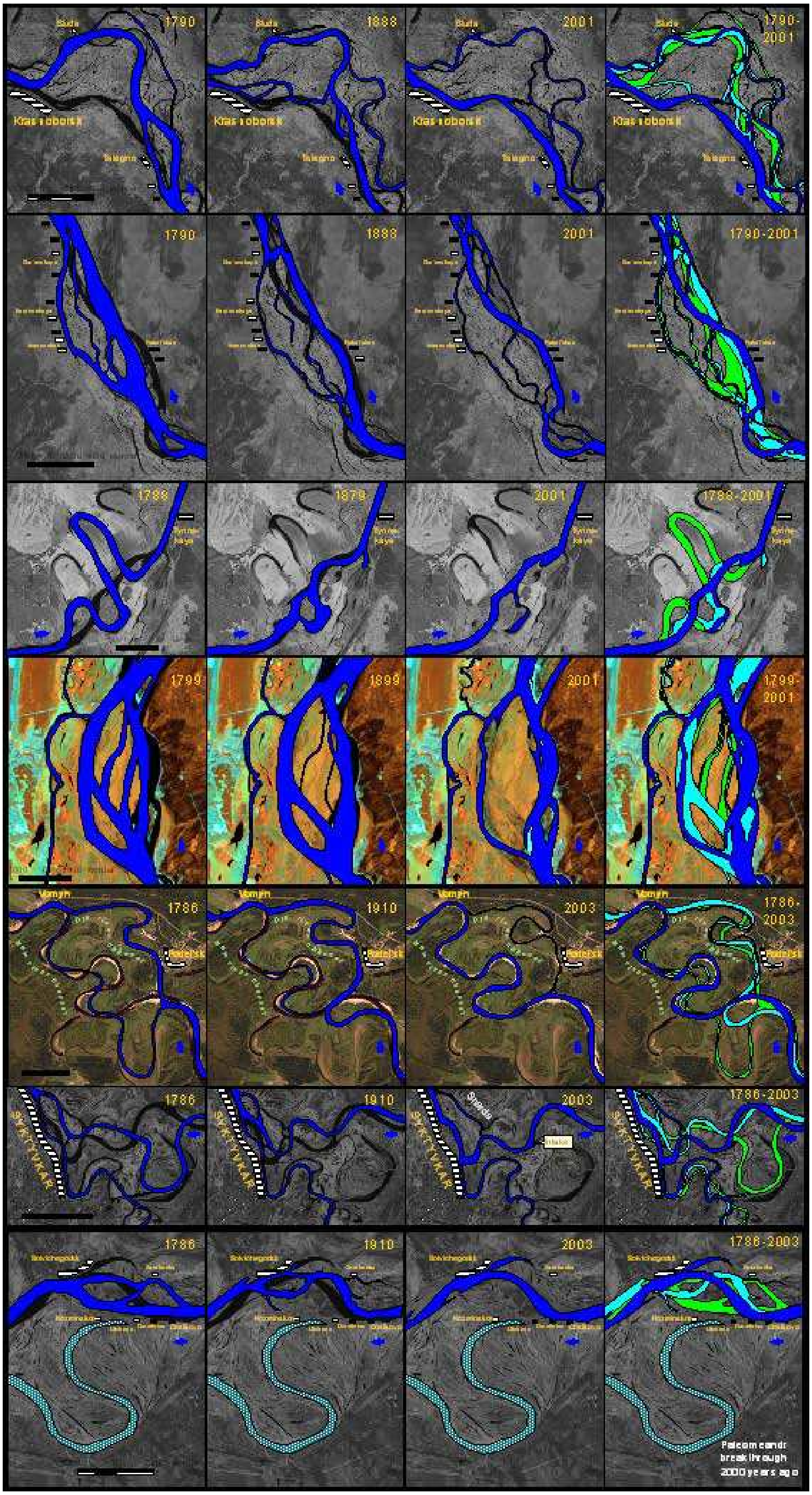


Fig. 1. River channel changes from the 18th century until present: **(a, b)** Severnaya Dvina River; **(c)** Oka River; **(d)** Ob River; **(e, f, g)** Vychegda River.

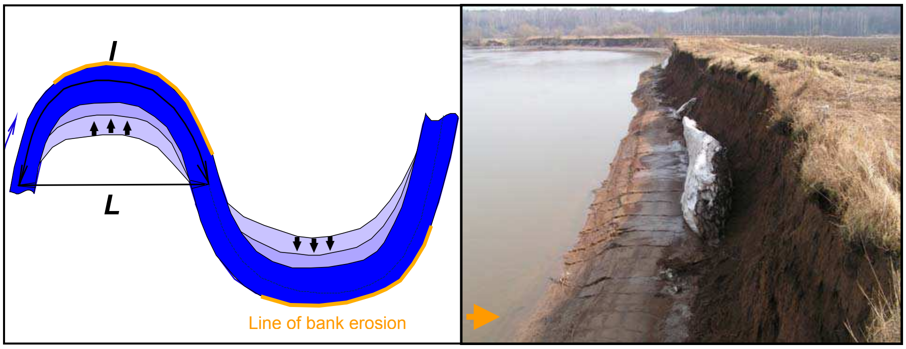


Fig. 2. Meander deformation: left – increasing of curvature. The main meander parameters: l – length, L – step, r – radius, h – sag, l/L – curvature, r/h – index of form; right (photo) – typical case of erosion of upper part and low wing of meander (the Moscow River).

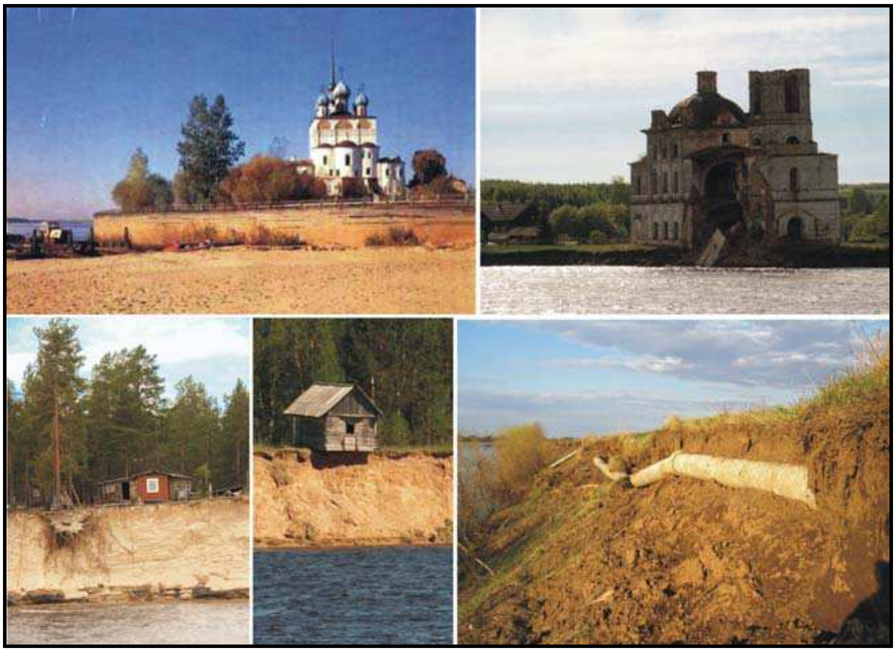


Fig. 3. Destroy of buildings as a result of river bed migration (photo taken by A. Zavadskiy).

have been constant during the last centuries. Water runoff fluctuations (periods and cycles), over millennia, centuries, years and within the year, are main changing factors. Combination of these factors in concert with anthropogenic impact determines trend and intensity of channel formation.

5.1 Major constant regional factors

We determine that major constant regional factors affecting the rate of processes are channel formative discharge and channel stability. Channel formative discharge is water discharge which leads to most significant channel change. On selected rivers channel formative discharge is usually observed during high floods. The most important factor is whether or not overflow land flooded. On rivers where overflow land is flooded during spring, flood magnitude and duration of peak discharge play a major role. The most intensive channel change has been observed in years with high runoff after flooding of overflow land. In case height and duration of flood was sufficient for spur erosion, meanders stretch and migration of braid channel was observed.

Channel stability depends mainly on river bed angle and sediments size. For example, meander formation rate is up to 20 and more metres per year on the weakly stable Vychegda River, up to 6 m per year on the rather stable Oka River, and up to 1.5 m per year on the stable Moscow River. As a result, about half of existing meanders have been stretched during the study period on Vychegda, about a quarter on Oka, and just sporadic cases on Moscow. On the basis of these data, we determined the duration of such long-scale processes as the meander formation cycle (Table 2).

Table 2. Main regional constant factors and the rate of meandering channel formation.

River	Main factors		Rate of bank erosion, average (maximum), m per year	Percentage of meander stretching, %	Average time of meander "life", years
	Channel stability	Channel formation discharge is observed			
Vychegda	Weak	when river overflow its bank	4–5 (20–25)	50	400–450
Oka	Average	when river overflow its bank	2–3 (6)	26	600–700
Moscow	Average	inside the channel	0.5 (1.5)	4	900-1000

Meander formation cycles range from 400–450 years for Vychegda, 600–700 years for Oka to about 1000 years for most part of the Moscow River, where channel formation discharge is concentrated within flood edges.

The duration of branch mastership on braiding rivers also depends on channel stability. On the weakly stable Severnaya Dvina River the main stream migrates from one branch to another within a few years, whereas on the stable Ob and Tom Rivers several branch systems remain stable for centuries. The most stable are braiding channels, when the main stream is located under bed-rock bank.

Thus, the most intensive meander and braid change is observed on rivers (or river parts) with weakly stable channel and overflow land flooded during the annual flood.

5.2 River runoff change

River runoff fluctuation is the main factor of channel transformation. River runoff changes were assessed for two periods: before and after hydrological network creation, at the turn of the 19th to the 20th century. For previous periods we determined water discharge using methods of regional reconstructions and historical data, first of all high water level marks for selected rivers (Fig. 4a). For most rivers on the Russian Plain, we observed a single-peak discharge pattern during spring snow-melt flood which determines annual runoff (Table 1). We derived annual discharge value and its long-term fluctuations from spring flood maximum discharge data. For the Severnaya Dvina catchment area we identified a decrease of peak discharge since the 18th century and thus suggested a decrease of runoff accordingly (Fig. 4a).

Reconstruction of the Moscow river runoff is presented on Fig. 4b (Klige, 1998). It was compiled using data about extraordinary events. Cycles of low and high runoff can be traced here, like on most of the rivers. During high runoff periods intensity of river bed processes increases, meanders move downstream due to erosion of their low wings. When runoff is below average meanders develop primarily through lateral erosion on the crest of the meander.

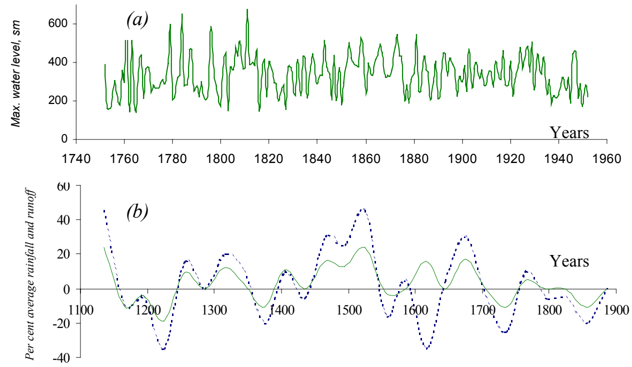


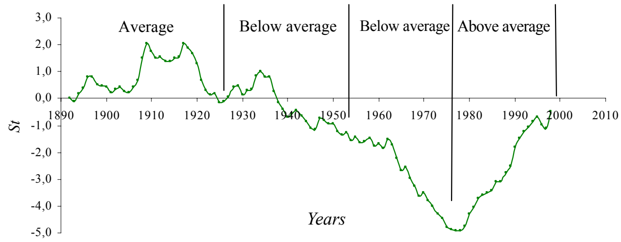
Fig. 4. Long-term runoff fluctuations of: **(a)** high water level marks of the Severnaya Dvina River since the mid-18th century; **(b)** Moscow River runoff cycles in the last millennium (average 550 and 190 mm) (Klige, 1998).

Another type of long-term runoff reconstruction is based on geological and geomorphological data. So for the Ob catchment area we used A. Shnitnikov's (1957) runoff reconstruction based on fluctuations of water level marks of West Siberian lakes and archival material.

For the period of regular hydrological observations, started in Russia about 100 years ago, runoff fluctuations were estimated using cumulative curves, which demonstrate periods of low and high runoff (Fig. 5). Thus we determined the duration of periods with low and high runoff and defined runoff fluctuation cycles ranging from years to decades.

6 Results

Long-term runoff fluctuations as well as regional factors determine trend and intensity of channel development and reveal certain regularities. During the periods of runoff prevalence above average on Russian and West Siberian Plains (i) intensification of channel formation, (ii) majority of drastic channel changes: runoff migration between branches and



Survey date	1879	1925	1953	1976	1999
Water runoff period	Average		Below average		
		Below average		Above average	
Index l/L	1,88	1,93	1,94	1,95	2,02
Increase of l/L	0,05	0,01	0,01	0,07	

Fig. 5. Cumulative curve of the Oka River runoff and change of meander formation rate. When runoff is above average, meander curvature (l/L) increases. St – non-dimensional deviatoric index of runoff.

meanders stretching, and (iii) increase of meander size, can be observed.

The increase of water discharge leads to intensification of the channel formation process, with rates of meander formation growing notably. Comparing series of maps (scale 1:10 000) and measuring the main parameters allow us to determine the intensity of meander formation in periods of different runoffs. Results of a case study for the Oka River are presented on Fig. 5. Periods with runoff above average are remarkable by high rates of meander formation. Therefore, for periods of runoff above average, the curvature increases more rapidly, and the index l/L shows a marked growth (Fig. 5).

Most cases of drastic river channel changes, i.e. runoff migration between branches and meanders stretching, were observed just for years with high runoff. Long-term cycles of meander evolution and braiding usually finish due to rapid meanders outbursts and runoff transfer from one branch to another.

The major high scale deformation of the Severnaya Dvina river bed and runoff migration from the main channel to the left branch were observed during high runoff periods in late 19th – early 20th centuries (Fig. 1a). Cases of meander series stretching on the Oka River (at the end of the 19th century) and the Vychegda River (in the middle of the 19th century) were also observed when runoff was above average (Fig. 1c, e).

During periods of low runoff, when spring floods are neither high nor long, cases of meander stretching are scarce. We obtained statistics for the Severnaya Dvina catchment area. Here peak discharge decreases since the end of the 18th century, being accompanied by reduction of meander stretching and runoff migration twice between branches. When peak discharge decreases, the discharge in minor branches also decreases (Fig. 1a, b).

6.1 Determination of water runoff during the past as a result of studying meander size changes

Weakly stable river channels show a clear and rapid response to runoff changes. Thus we may assess the reaction of meander size to runoff changes and deduce relationship between these parameters.

In order to determine water runoff in the past, we chose the weakly stable meandering channel of the Vychegda River. Anthropogenic impact is practically absent here, providing the chance to reveal natural trends.

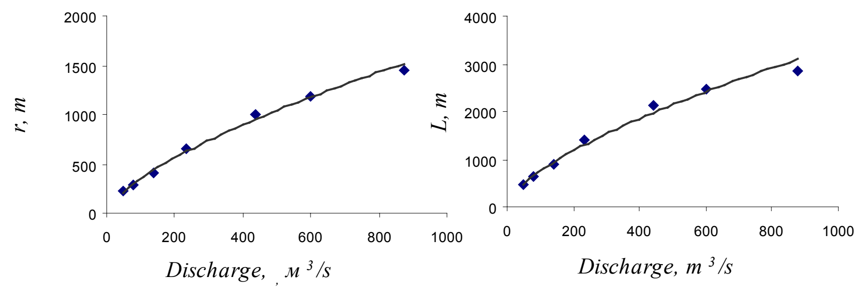
The direct relation between meander size and water runoff is well known: large rivers develop large meanders (Chalov et al., 2004). Figure 6 shows the relationship between runoff value and meanders size for the Vychegda River. The increase of the meander size is accompanied by the increase of the annual discharge downstream. We may assess the runoff during the past, using this relationship between discharge and meander size for temporal reconstruction. Thus, runoff decrease in the Severnaya Dvina basin since the 18th century up to 20–30% is revealed. This is corroborated by runoff decrease in secondary branches and by reduction, in two cases, of meanders stretching and runoff migration between branches since the 18th century (see above).

6.2 Forecast of channel formation as a result of runoff change

We can use cases of high scale runoff change to estimate its impact on river bed processes and to verify the forecast hereby. Water transfer from one basin to another may lead to runoff changes compared with conditions over geological periods. The Moscow River runoff increased twice since 1937 due to water transfer from the Volga basin. Hereupon we observe active river channel transformation under increased runoff (Kargapolova and Zavadskiy, 2006). Natural changes since 1772 and size enlargement after runoff transfer are shown on Fig. 7. After runoff increases, meanders generally change direction of their development from lateral to longitudinal, enlarge and change shape and parameters (Table 3).River banks are subject to erosion, and this process is currently ongoing. Small meanders in the low part of flood plain are stretched. As a result, now we observe process of channel fitting to increased water discharge. We tried to estimate the duration of the meander formation process and the final meander size. As well as for the Vychegda River we used relationship between water discharge and meander size for temporal reconstruction for the Moscow River. Knowing increased water discharge we have calculated according meander size. It was determined that due to runoff transfer meander size should increase 15–30%. In case of stable conditions meander size growth will be terminated within 100–200 years.

Table 3. Change of channel parameters after water transfer. Size of meanders (r, L) increase; steepness (l/L) reduce.

Date	Water discharge, m^3/s	Channel parameters						
		l/L steepness	r/h index of form	r radius	l length	L step	h seg	B width
1930	62	1.61	0.95	321	124	779	395	121
1966	98	1.59	1.05	335	123	781	385	130
1991	110	1.55	1.12	336	122	788	370	188



Date	Index of meander size		Average water discharge
	r	L	
1786	690	1510	750
1910	620	1360	530
1987	660	1400	600

Fig. 6. Relationship between average water discharge and meander size for the Vychegda River: r – radius, L – step of meanders.

7 Conclusions

We determine the impact of long-term runoff fluctuations in concert with regional factors on river channel evolution. We determine trends, cycles and the intensity of braiding and meandering channel changes under different conditions.

Most intensive changes of meanders and braids are observed on rivers: 1. with weakly stable channel, 2. where duration of channel formative discharge is high and overflow land is flooded for a long time, 3. in periods of runoff above average.

We show that in periods with high runoff (above average):

– the rate of channel formation increases;

– the majority of drastic channel changes, such as runoff migration between branches and meander stretching, is observed;

– the meander size increases.

Based on relationship between meander size and water runoff, we estimated the Vychegda River runoff over the past 200 years. The runoff in the Severnaya Dvina basin was shown to have decreased by up to 20–30% since the 18th century. In addition, a forecast of river bed transformation was made for the Moscow River, where runoff has increased twice due to water transfer. A meander size increase of up to 15–30% is predicted for the next 100 to 200 years.

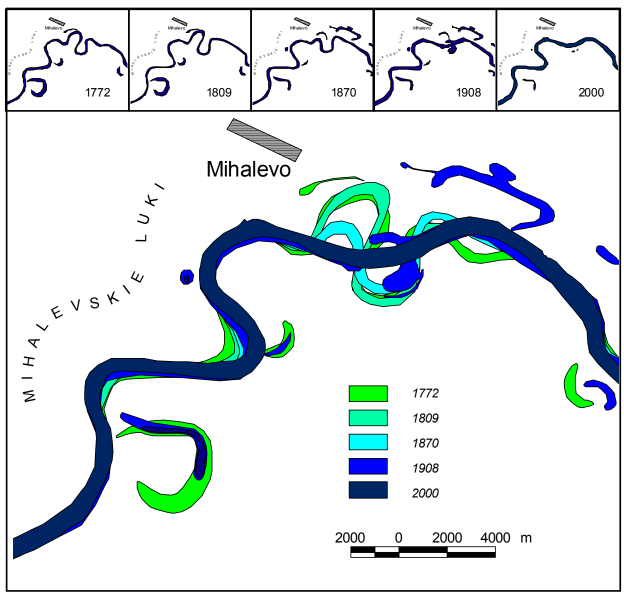


Fig. 7. Position of the Moscow River channel before (1772, 1808, 1870, 1908) and after (2000) anthropogenic runoff transfer.

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